Efficient Solar Driven Air Conditioning System for Hot Climate: Case Study of Doha

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Abstract

An advanced thermal solar driven air conditioning system for hot climate is described and a steady state thermodynamic model is used to predict its performance by using weather data for Doha (Qatar). The proposed system combined both Organic Rankine Cycle (ORC) and conventional mechanical Vapour Compression Cycle (VCC) whereby the expender (Turbine) is coupled to the compressor. Both cycles operate with ammonia refrigerant. For the same collector surface area (20 m^2), the corresponding average daily cooling production is high with Evacuated Tube Solar Collector (ETSC) compared to Flat Plate Solar Collector (FPSC): ranging from 3.4 kW (in July) to around 7.6 kW (in April) for FPSC and from 4.5 kW (July) to around 10.2 kW (in April) for ETSC. The maximum values of COPs obtained (0.50 to 1.60 with an optimum driving temperature of about 118^{o}C) are overall above those of standard heat driven systems such as absorption or adsorption refrigeration systems (typical maximum values range: 0.4 to 0.8).

Keywords: Solar Energy, Air Conditioning, Organic Rankine Cycle, Vapour Compression Cycle.

1. Introduction

The hot climate regions (typical ambient temperature above 30^{o}C) often require air conditioning in buildings for better comfort (typical environment temperature above 22^{o}C and 50% relative humidity). So far the air conditioning in buildings are mainly electrically driven leading to the increase of fuel consumption therefore the increase of carbon footprint when power stations burn fossil fuel. Equally, the hot climate regions do have higher solar thermal energy radiation that could be converted into useful cooling for air conditioning. This paper explores the potential use of an advanced thermal solar driven air conditioning system for hot climate that is similar to Qatar with a ground-measured annual average solar radiation of 2113 kWh/m^2/year **[1]** and the highest annual carbon footprint estimated to 44.4 metric tons of CO_2/person/year **[2]**. For illustration of performance of the proposed system, the city of Doha is chosen for case study.

2. System description

The conceptual proposed system combines both Organic Rankine Cycle (ORC) and conventional mechanical Vapour Compression Cycle (VCC) for refrigeration **[3]**. There are two distinctive and separated loops operating both with Ammonia refrigerant (R717): the ORC loop and the VCC loop **(Fig. 1)**. The ORC loop consists of a boiler embedded within a thermal solar energy collector, an expender or turbine, a condenser and a liquid pump. The solar collector could either be flat plate type (FPSC) or evacuated tube type (ETSC). The VCC loop has the conventional layout with a condenser, an expansion valve, an evaporator and a mechanical compressor. The turbine is coupled to the mechanical compressor: it is therefore driven by direct expansion of high pressure and high temperature of saturated refrigerant gas coming out of the boiler operating with solar thermal energy gained. The condensers of both ORC and VCC loops are tubular-finned type of heat exchangers that are laid out in parallel in order to operate with a single fan. As optional consideration, each loop (ORC and VCC) could also include an Ammonia liquid receiver located outlet of each condenser.

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3. Thermodynamic model

A thermodynamic model of the proposed system, operating with Ammonia refrigerant (R717), is used to predict key performance indicators like COPs and cooling power output when the Ammonia steam driving temperature is ranging between 30ºC to 130ºC (corresponding to about the critical temperature of Ammonia refrigerant). As example, both ORC and VCC are illustrated on a *Pressure-Specific Enthalpy or P-h* diagram shown in **Fig. 2**. Both expander (Turbine) and compressor are assumed to have an isentropic efficiency of 80% each with transmission coupling efficiency of 80%. Furthermore, both sub-cooling and superheat are 4ºC and 7ºC respectively on the mechanical vapour compression machine. Flat plate and evacuated tube types of solar thermal collector (FPSC and ETSC respectively) are used with typical average thermal efficiency of 55% and 75% respectively. The reference surface area taken for each collector is 20 m^2.

4. Simulation Results and Discussions

The simulations were carried out using Doha weather data **[4]** with an evaporating temperature of 15ºC and a condensing temperature that is about 5ºC above the ambient temperature. **Fig. 3 and Fig. 4** show monthly mean ambient temperature and monthly global solar radiation respectively. The energy balance on the solar thermal collector/boiler was achieved within about ±2% throughout the full range of the operating boiling temperature. For that purpose, the final input value of refrigerant mass flow rate on the Organic Rankine Cycle (ORC) will vary not only with the type of collector but also with the operating month as shown in **Tab. 1**. We have also assumed that the ammonia liquid flowing across the pump (located between the Condenser and the Collector/Boiler) is uncompressible. Simulations are focused between April and November where the cooling demand is most crucial in buildings (as the ambient temperature is above 22ºC corresponding to normal comfort temperature with 50% Relative Humidity). Furthermore the monthly solar heat rate gained to operate the system will also take into account the effective sunshine duration as illustrated in **Fig. 5**.
Fig. 6 and **Fig. 7** show the predicted performance indicators with Flat Plate Solar Collector (FPSC) and Evacuated Tube Solar Collector (ETSC) respectively: the best performance are in April when the ambient temperature is relatively low (about 26.4ºC) while low performance are in June, July and August when the ambient temperature is relatively high (typically 35ºC). Regardless the type of solar collector, the COPs are unchanged (ranging from 0.15 to 1.2) since they correspond more to the intrinsic characteristics of conventional mechanical Vapour Compression Cycle (VCC). There is an optimum driving temperature at around 118ºC that is specific to the refrigerant used and the nature of Organic Rankine Cycle itself. As expected for the same collector surface area, the corresponding average daily cooling production is high with ETSC compared to FPSC: ranging from 3.4 kW (in July) to around 7.6 kW (in April) for FPSC and from 4.5 kW (July) to around 10.2 kW (in April) for ETSC. For the same optimum driving temperature, the average daily COP is ranging from about 0.53 (July) to 1.2 (November).

5. Conclusion

The maximum values of COPs obtained (0.50 to 1.60 with an optimum driving temperature of about 118ºC) are overall above those of standard heat driven systems such as absorption or adsorption refrigeration systems (typical maximum values range: 0.4 to 0.8). However the optimum driving temperature leading to better performance indicators will require the collector/boiler to withstand high pressure as 88 bar which could impact on the proposed system design specifications and cost. This means that there is trade-off between performance indicators and the high pressure on the Organic Rankine cycle loop in particular. Overall the proposed conceptual design has good potential not only for solar driven air conditioning system in building but also for combined heat and cooling production in Small and Medium-sized Enterprises (SMEs).

6. Further work

The current work will be refined by using solar collector/boiler with variable efficiency function of both incident solar radiation and temperature difference between the collector/boiler and the surrounding ambient air. Further work such as the mitigation of intermittent solar energy daily availability (about 8 to 12 hours), the development of hermetic turbo-compressors (combined Turbine and Compressor), and detailed cost and CO2 emission saving analysis of the overall system are still needed. Furthermore there are still some scopes of exploring different refrigerants on both ORC and VCC loops.

7. References

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[2] Yousef Alhorr, Eiman Eliskandarani, Esam Elsarrag, Approaches to reducing carbon dioxide emissions in the built environment: Low carbon cities, *International Journal of Sustainable Built Environment*, 3, pp. 167–178, 2014.

[3] Z. Tamainot-Telto, Advanced heat driven hybrid refrigeration and heat pump systems, *Proc. 12th IEA Heat Pump Conference (HPC 2017)*, Rotterdam (The Netherlands), 15-18 May 2017.

[4] http://qweather.gov.qa/ClimateInfo.aspx (Access date 10/10/2017).

Tab. 1: Doha weather data [4] and estimated value of Ammonia refrigerant mass flow rate on the Organic Rankine Cycle (ORC) and conventional Vapour Compression Cycle (VCC)

Month	April	May	June	July	August	Sept	Oct	Nov
$T_{average}$ (°C)	26.4	31.8	34.5	35.3	34.8	32.8	29.5	24.6
Q_r(kWh m^{-2})	5.7	6.2	6.5	6.1	5.8	5.5	4.8	4.1
Sunshine (h)	9	10.6	11.5	10.6	10.6	10.2	9.9	9
m_{fFPSC}(kg h^{-1})	21.96	20.88	20.16	20.88	19.8	19.08	16.92	15.84
m_{fETSC}(kg h^{-1})	29.88	26.28	27.72	28.44	27.00	25.92	23.40	21.60

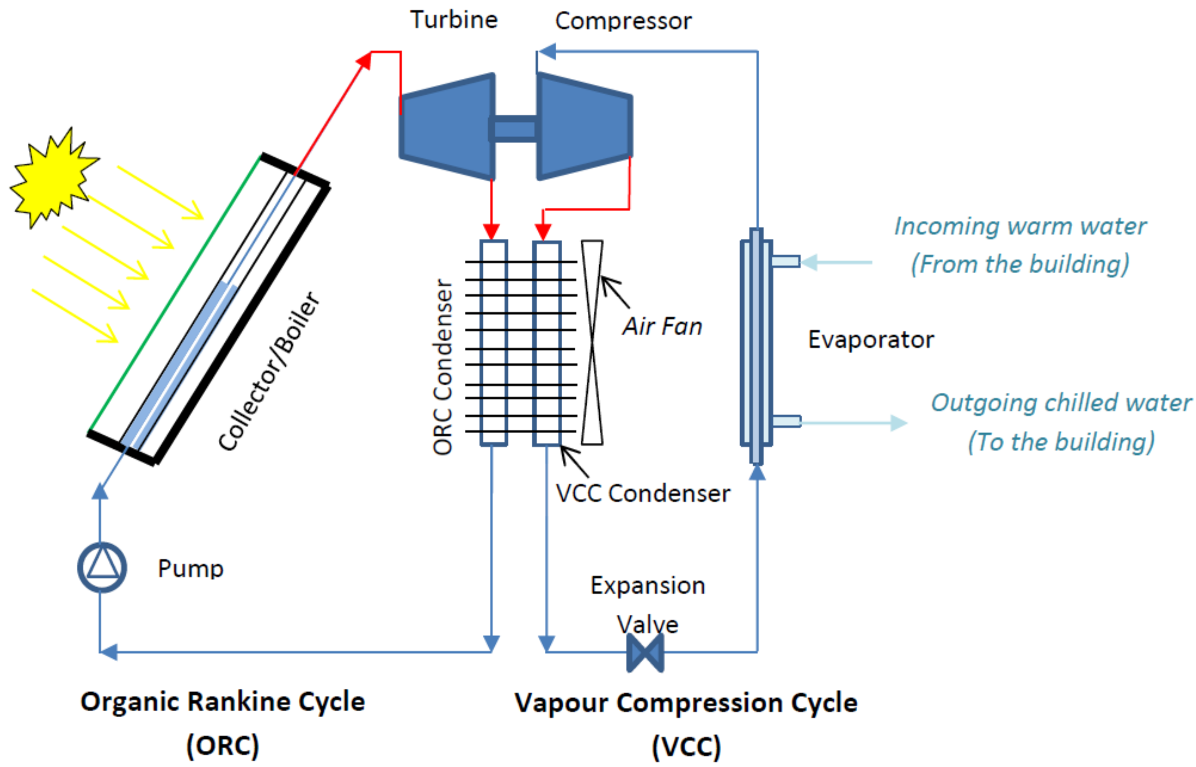

Fig. 1: Illustration of system combining Organic Rankine Cycle (ORC) and conventional Vapour Compression Cycle (VCC)

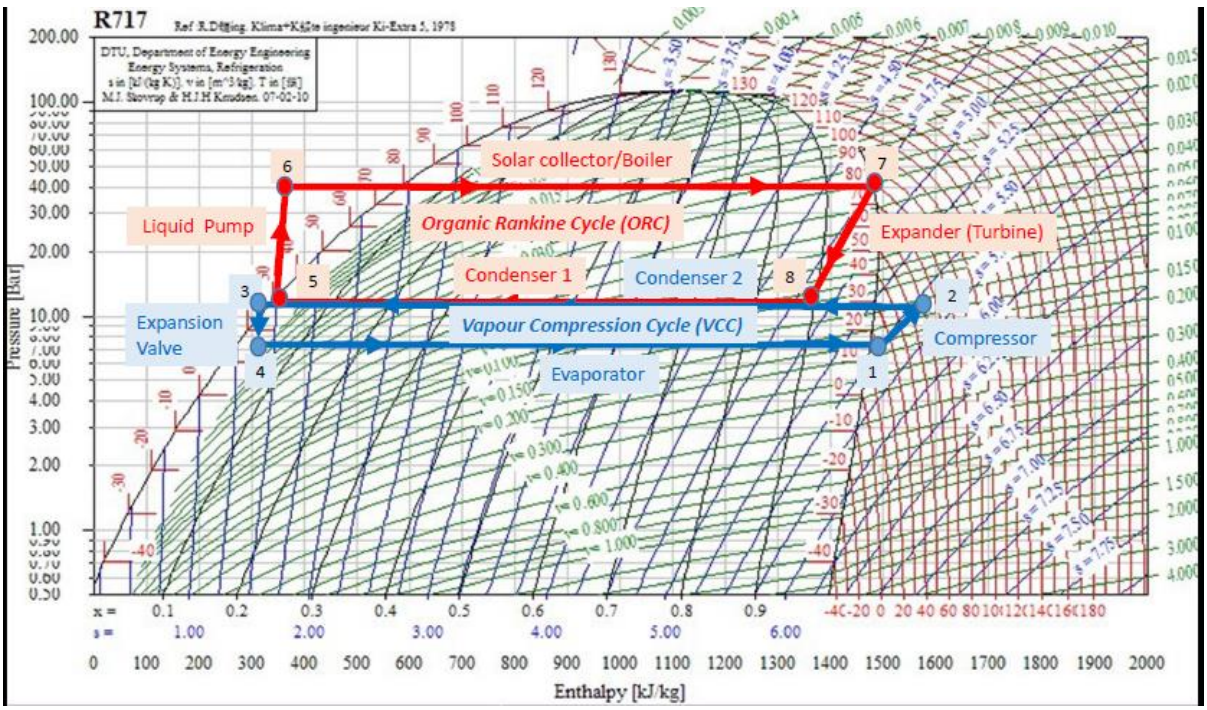

Fig. 2: Illustration example of both Organic Rankine Cycle (ORC) and Vapor Compression Cycle (VCC) with $T_{Evaporator}$= 15ºC, $T_{Condenser}$= 30ºC and T_{Boiler}= 80ºC

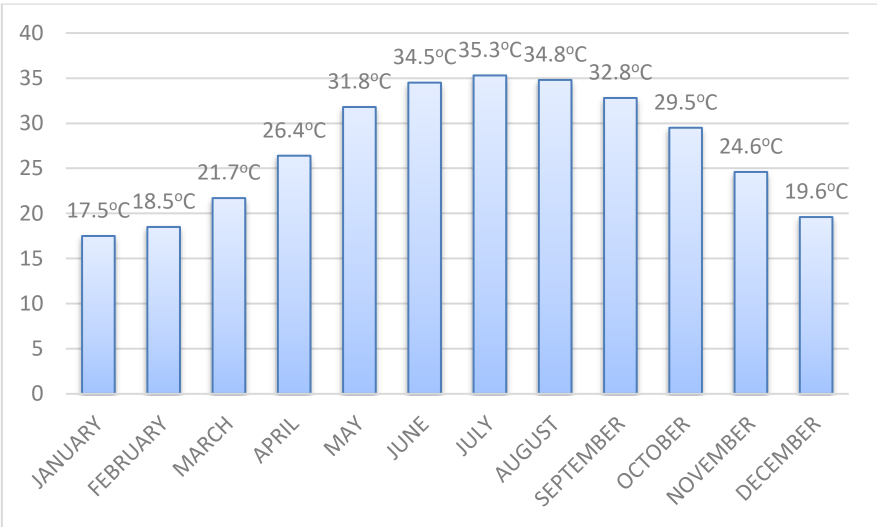

Fig. 3: Daily mean temperature for Doha, Qatar [4]

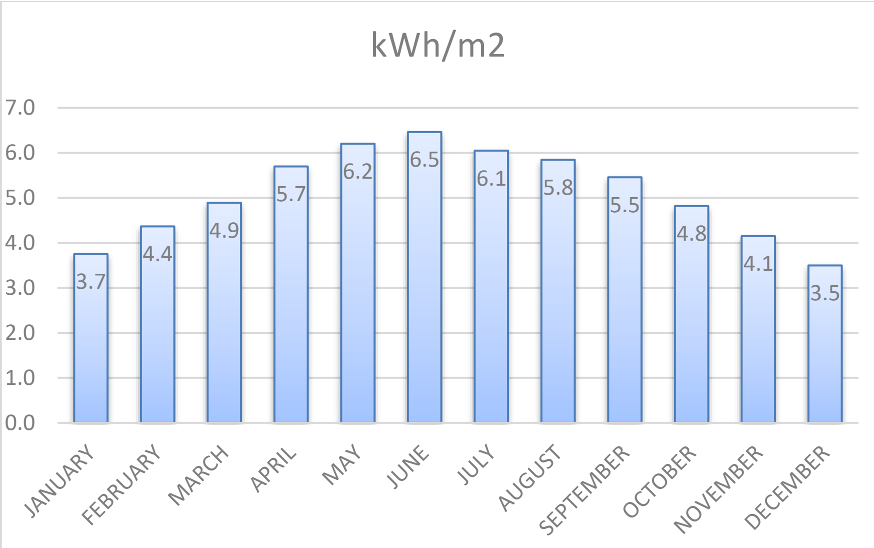

Fig. 4: Daily mean solar radiation for Doha, Qatar [2]

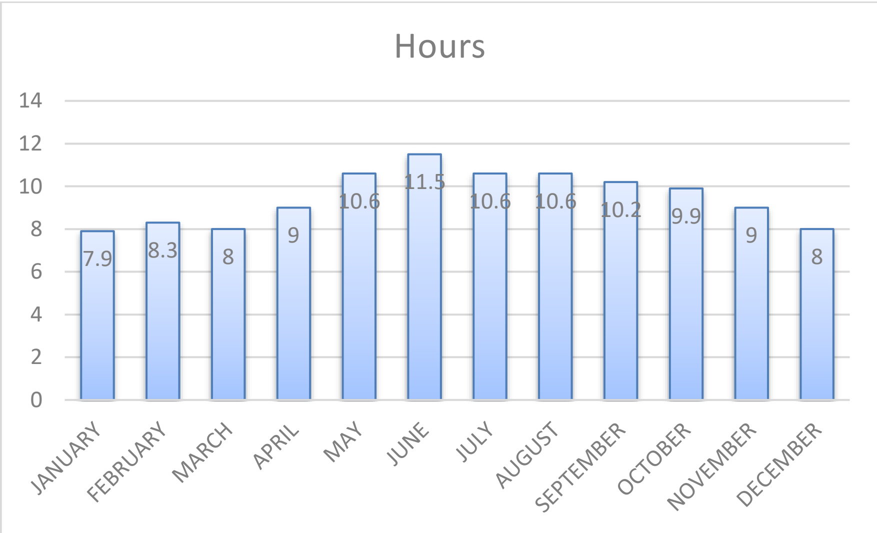

Fig. 5: Daily mean sunshine duration for Doha, Qatar [2]

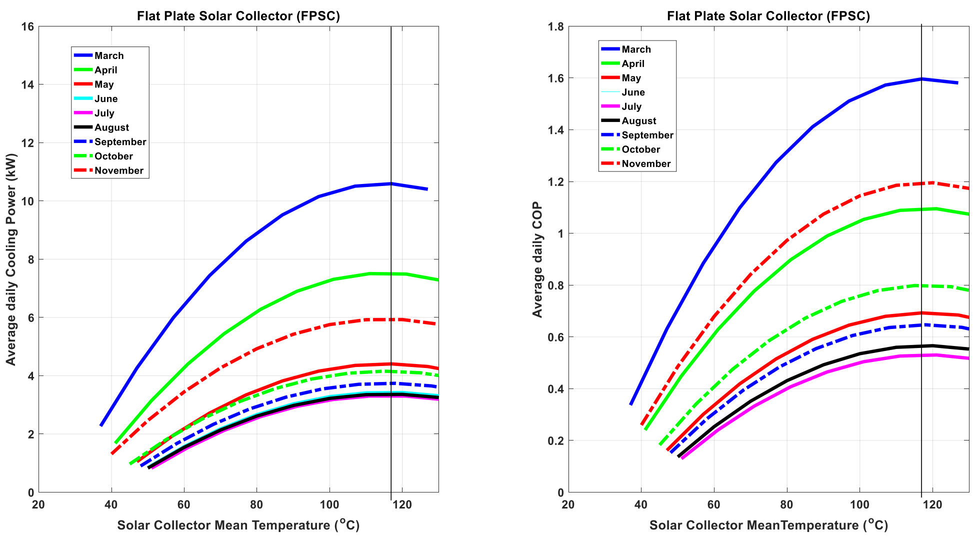

Fig. 6: Key performance indicators with Flat Plate Solar Collector (FPSC)

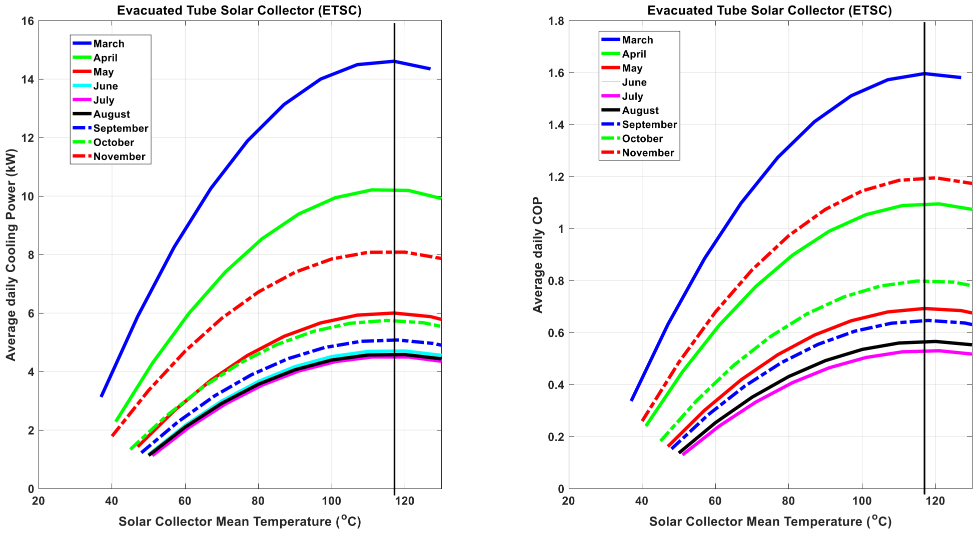

Fig. 7: Key performance indicators with Evacuated Tube Solar Collector (ETSC)